High Energy Density Laboratory Plasma (HEDLP) Research Needs Workshop (ReNeW)

A Status Report

There Are Many Intriguing Scientific Questions to Address!

D. Hammer/R. Rosner
Co-chairs

FESAC, Gaithersburg, MD

Tuesday, March 9, 2010

What we will talk about …

- A very quick overview of the ‘boilerplate’
  - Charter, recent history, status, …
- Our goals/aims
- The Report’s structure
- Details
  - The 5 Questions
  - The 6 Sub-disciplines
  - The 4 ‘cross-cutting’ disciplines
  - What’s been said before – and what hasn’t …

Our Charter

Department of Energy
Washington, DC 20585

July 9, 2009

Dear Colleague,

Letter signed by Dr. Christopher Deeney (NNSA) and Ed Synokowski (SC/OFES)

"The Office of Fusion Energy Science (SC/OFES) and the National Nuclear Security Administration (NNSA/DP) plan to hold a Joint Research Needs Workshop on High Energy Density Laboratory Plasmas (HEDLP) from November 15-18, 2009 [in Rockville MD]."

"In January this year, the Fusion Energy Sciences Advisory Committee (FESAC) submitted its report to the U.S. Department of Energy on **"Advancing the Science of High Energy Density Laboratory Plasmas,"** prepared by its Panel on High Energy Density Laboratory Plasma, chaired by Professor Riccardo Betti of the University of Rochester.

http://www.science.doe.gov/ofes/FESAC-HEDLP-REPORT.pdf

This report: (1) identified the compelling scientific opportunities for research in fundamental HEDLP and (2) identified the scientific issues of implosion and target design that need to be addressed to make the case for inertial fusion energy as a potential energy source. As recommended by FESAC, we are jointly sponsoring a **Workshop** with the **goal of examining these research opportunities in depth and deliberating on the research needs in order to pursue these opportunities**. The workshop output will be a **concise authoritative report** suitable for wide distribution. **The report of the Workshop will provide technical advice to be used as guidance in strategic planning for the joint program by OFES and NNSA.**"

Charter (Cont'd)

"The OFES Technical Lead … is Dr. Francis Thio, and the NNSA Technical Lead … is Dr. Dillon McDaniel. Professor Robert Rosner of the University of Chicago and Professor David Hammer of Cornell University have agreed to Chair and Co-Chair the Workshop."

" …. the FESAC HEDLP Panel identifies **six scientific sub-disciplines:**

- **High Energy Density (HED) hydrodynamics,**
- **Nonlinear optics of plasmas**
- **Relativistic HED plasma and intense beam physics**
- **Magnetized HED plasma physics**
- **Radiation-dominated dynamics and material properties**
- **Warm dense matter"**

" …. the Workshop will address the opportunities and needs of these six sub-disciplines and cross-cutting issues using a panel structure." The need was recognized for cross cutting panels for

- Connecting HEDLP research to other areas of physics and science in general
- Computing
- Diagnostics
- Research Infrastructure
- High-Z multiply Ionized HED Atomic Physics

There is considerable 'Recent History'

HED-focused reports:

- NAS/NRC Report (Davidson): *Frontiers in High Energy Density Physics, The X-games of Contemporary Science* (2003).
- NSTC – Nat'l Task Force on HEDP (Davidson): *Frontiers for Discovery in High Energy Density Physics* (2004)
- DOE/SC (Browne-Rosner): *Summary of a Workshop on Opportunities for High Energy Density Laboratory Plasma Science* (2007)
- NSTC/IWG (Kovar-Keane): *Report of the Interagency Task Force on High Energy Density Physics* (2007)
- OFES/FESAC (Betti): *Advancing the Science of High Energy Density Laboratory Plasmas* (2009)

Related reports:

- DOE/NSF: *The Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and technology using the Brightest Light Known to Man* (2002)
- NAS/NRC Report (Turner): *Connecting Quarks with the Cosmos* (2003)

Status Report on the HEDLP ReNeW: Where are we?

- **We followed a standard Research Needs Workshop process developed by SC/BES (Basic Energy Sciences) as per our charter**
  - See http://www.sc.doe.gov/bes/reports/files/BRN workshops.pdf)
- **Prior to our workshop meeting we prepared 'working papers' for our disciplinary and cross-cutting panels**
  - "1-pagers"
  - "5-pagers"
- **The workshop took place 15-18 November 2009**
  - 138 of your colleagues (56 from NNSA labs, 51 from universities [42/9], 9 NRL/LBNL, 3 Small Business, 19 "Other")
  - 22 panel leads and co-leads, 114 panel members on 11 panels
- **Most chapters have been finished by the panels, and edited by the co-chairs**
  - Science editing (T. Rothman/Princeton) and production (Argonne) about to get underway

What were our goals for the HEDLP ReNeW: 1

- **To produce an advocacy document, not a review**
  - We are not a FACA-governed advisory committee
- **To lay out the research needs for the most interesting and important opportunities** in
  - fundamental research on extreme states of matter
  - research in pursuit of IFE
  - research that could contribute to the development of other applications and/or fields that are not part of the NNSA mission (e.g., lab astro, wakefield accelerators, WDM, …)

What were our goals for the HEDLP ReNeW: 2

- **To determine**: ***What interesting physics can be done that we are not already doing with the the HED facilities we have now if we had a growing HEDLP program?***
  - What more could we do in ~5 years with upgrades to these facilities?
  - What could we do on a 10-15 year time scale if new facilities that can increase our reach into the HED universe significantly were built?
  - Can we expect to be testing the practicality of IFE in the 10-15 years?

What were our goals for the HEDLP ReNeW: 3

- **To identify barriers to carrying out the best possible HED research**
  - Infrastructure
  - Computing
  - National security and classification
  - Export controls
  - Institutional boundaries

Here's our Report's Structure …

- Executive Summary: Scientific American level
  - The five questions of HEDLP
  - The special nature of the field of HEDLP
  - The sub-disciplines of HEDLP
  - The cross-cutting subjects of HEDLP
- Sub-discipline chapters: Physics colloquium level
  - Sidebars: Scientific American level

N.b.: We believe that this Report is not about facilities … it's about the science … and as far as facilities are concerned, we were both 'ecumenical' and 'sparse' …

The five questions of HEDLP

- How does the exotic behavior of dense collections of electrons, ions and photons arise?
- What can creating cosmic conditions in the laboratory reveal?
- Can transient intense flows of energy and particles, unconstrained by conventional material limits, be manipulated and exploited?
- Can the interactions of matter under extreme conditions be controlled to enable practical inertial fusion energy?
- How does self-organization arise within high-energy density matter?

The special nature of HEDLP

- Connections between HED science and other fields of physics
- The Elephant in the Corner: The Relationship between HEDLP and the Nuclear Weapons Program
- A history of reviews of HEDLP and the process we followed

Our Report's Structure: The sub-disciplines

- **HED hydrodynamics**
  - *How is hydrodynamics altered by the distinct properties of high energy density systems? Can understanding HED hydrodynamics help to control HED plasmas in the laboratory and increase our understanding of cosmic phenomena?*
- **Magnetized HED plasma physics**
  - *How are magnetic fields created, and how do they evolve and affect the properties of HED plasmas?*
- **Nonlinear optics of plasmas**
  - *How does high-intensity radiation modify the behavior of high energy density plasmas?*
- **Radiation-dominated hydrodynamics and material properties**
  - *How is the behavior of HED plasmas altered in the radiation-dominated regime, and how do HED plasmas alter the propagation of radiation?*
- **Relativistic HED plasma physics & intense beam physics**
  - *How do plasmas dominated by relativistic effects behave?*
- **Warm dense matter**
  - *What are the material and transport properties of warm dense matter?*

Our Report's Structure: Cross-cutting Subjects

- Experimental Infrastructure
- High-Z atomic physics
- Diagnostics
- Computing

Selected Sub-disciplinary findings, opportunities and scientific questions 1 – HED Hydro

How is hydrodynamics altered by the distinct properties of HED systems? Can understanding HED hydrodynamics help us control HED plasmas in the laboratory and increase our understanding of cosmic phenomena?

- Understanding, creating & controlling HED plasmas allows us to study star matter in the lab.
  - Can we understand and control plasma instabilities, including RT, RM, KH … , under conditions relevant to fusion?
  - Can we use these understandings to achieve inertial confinement fusion?

Selected Sub-disciplinary findings, opportunities and scientific questions 2 – Magnetized HED

How are magnetic fields created, and how do they evolve and affect the properties of HED plasmas?

- Cosmic magnetic fields are ubiquitous, but their ultimate origins remain unknown
  - We can recreate cosmic conditions within the lab leading to the 'Biermann battery' effect – and perhaps even study turbulent dynamos
- Magnetic fields modify transport processes, accelerate particles, and exert body forces
  - HEDLP can create fusion-grade HED magnetized plasmas, model dynamical astrophysics phenomena (such as cosmic ray acceleration in magnetized shocks), and create extreme states of matter via compression

Selected Sub-disciplinary findings, opportunities and scientific questions 3 – Non-Linear Optics of HEDLP

How does high-intensity radiation modify the behavior of HED Plasmas?

- How can we achieve unique plasma states by self-organization of HED plasma in the presence of intense photon beams?
- How can we control and manipulate the intense flow of energy and matter in extreme states for ICF?
- Strategic use of non-linear optical interaction between lasers and HED plasmas can control the structure and evolution of the plasma, leading to, for example
  - energetic particles alteration of the development of plasma waves and instabilities,
  - focusing and amplification of laser radiation, etc.

  for fundamental studies and applications.

Selected Sub-disciplinary findings, opportunities and scientific questions 4 – Relativistic HED Plasmas

How do plasmas dominated by relativistic effects behave?

- The newest, more powerful lasers will enable investigation of extreme relativistic plasma conditions never before encountered.
  - We know little about such conditions, theories are untested, computational capabilities are not yet validated – and hence not yet credible. Is the physics all there?
- At the highest laser intensities, theory predicts that it will be possible to probe the nonlinearities of fundamental Quantum Electrodynamics.
  - It will be extremely interesting to see what surprises are in store for us as we try to reach the necessary intensities to do those experiments

Selected Sub-disciplinary findings, opportunities and scientific questions 5 – Rad-Dominated HED Plasmas

How is the behavior of HED plasma altered in the radiation-dominated regime, and how do HED plasmas alter the propagation of radiation?

- In this regime, photons can dominate the energy and/or momentum flows in the plasma
  - In the open literature, there is little about such conditions, theories are experimentally untested, computational capabilities are not yet fully validated – and hence not yet fully credible. Is the physics all there?
  - Such conditions obtain in exploding stars (e.g., Type II SN), nuclear weapons, …
- This regime can be exploited if it can be controlled
  - High-power lasers/pulsed power machines, to make 'star matter'
  - X-ray lasers, to produce WDM, probing physics of the interior of planets

Selected Sub-disciplinary findings, opportunities and scientific questions 6 – Warm Dense Matter (WDM)

What are the material and transport properties of WDM?

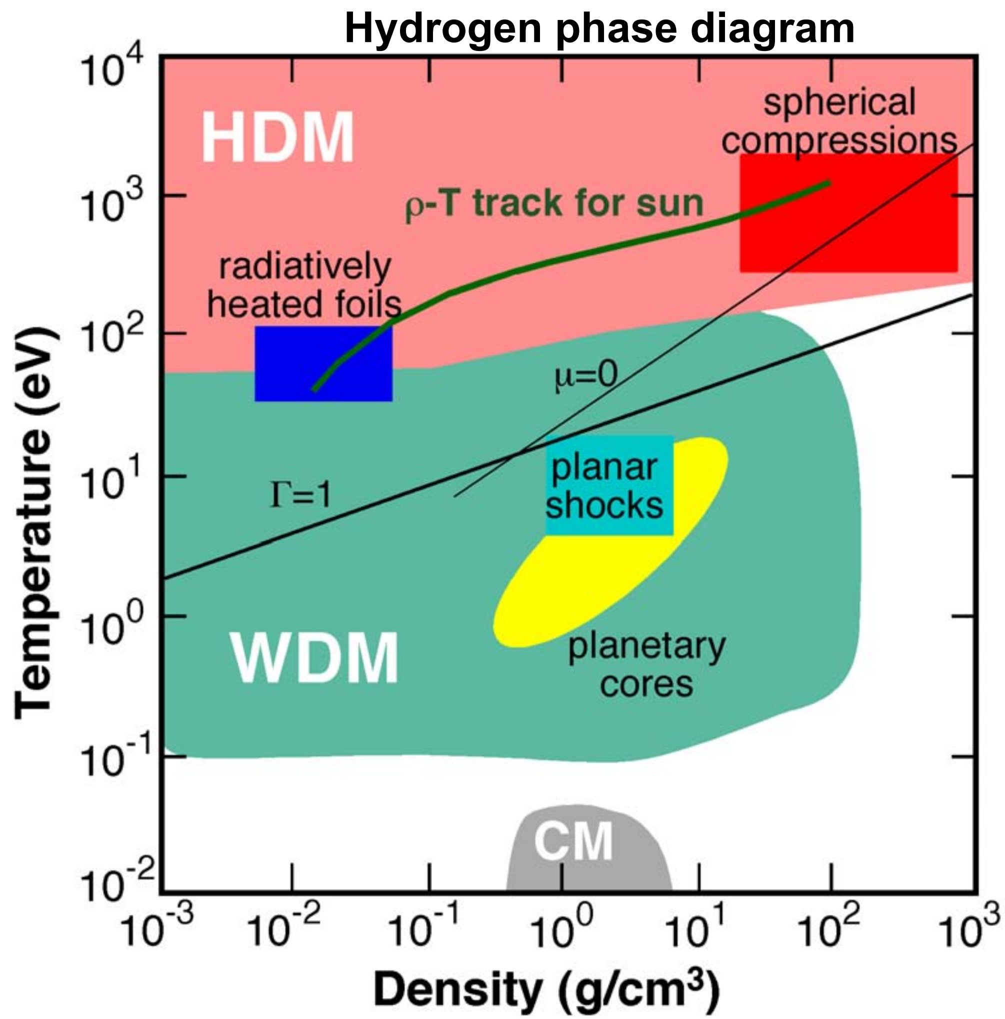
… but that is a pretty dry question, which may be why WDM is largely and conspicuously absent from academic physics

How about the following instead:

- ***What science underlies the violent formation of the planets?***
- ***What is the evidence that giant planetary impacts have played a role in solar system history?***
- ***Why is Saturn so warm, and why does Jupiter have such a large magnetic field?***
- ***Can we relate the birth of a star to the path to fusion in the lab?***
- ***What new Chemistry emerges in HED matter where core electrons are brought into the valence?***
- ***What novel phase transitions, such as liquid/liquid or metal insulator occur at high pressures and temperatures?***

HEDS covers a vast region in T-ρ phase space & numerous physical regimes (Slide from Dick Lee)

- **Hot Dense Matter (HDM):**
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, Z-pinches
  - Directly and indirectly driven inertial fusion experiments
- **Warm Dense Matter (WDM):**
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven inertial fusion experiments



Cross-Cutting areas 1 – Selected Findings

Infrastructure available now and in the near future can support a broad range of fundamental and applied science

- Fundamental studies in WDM → Relativistic HED research
- Applications ranging from ICF to wakefield accelerators
- Large-scale and small scale

Since the most interesting experiments always need a more powerful or more intense device, it would be good to have a prioritized program plan for "next facilities" based upon predicted research opportunities.

Cross-Cutting areas 2 – Selected Findings

Hi-Z Atomic Physics – an enabling science for HEDLP

- Emission and absorption properties are often the only window into an HED experiment → essential for some diagnostics
- Experiments in the lab can connect through observed emission and absorption spectra to distant astrophysical phenomena
  - Detailed physics and convection zone dynamics on the sun
  - Accretion disks around black hole

Cross-Cutting areas 3 – Selected Findings

Diagnostics for HEDLP experiments are extraordinarily challenging because of the extreme conditions:

"There is a merging and blurring of the experiment and the diagnostics, of the measurements to be made and the computational design of the experiment, and of the interpretation of the data from the diagnostics and the physics revealed by the experiment."

- ***Can we measure plasma parameters by enough independent diagnostics, or analyze the results from diagnostic devices with enough independent analysis tools, to achieve credible validation of computer simulations and a comprehensive understanding of an HEDLP experiment?***

Needs: Thomson Scattering (VUV → soft x-rays)

Energetic, short pulse x-ray sources (WDM → hot dense matter)

Advanced nuclear diagnostics for nuclear physics and for ICF

Cross-Cutting areas 4 – Selected Findings

Computing is at the heart of much of HED theory and modeling:

- Design, analysis and interpretation of experiments depend critically on computer modeling and simulation.
- Many issues for HED computing are common to other areas of physics – complex ("multi-physics"), non-linear, multi-time-scale, multi-spatial-scale
- However, there are a number of computing issues unique to HEDLP
  - **Classification**
  - **Export control**
  - **Unclassified but use-restricted**
- These restrictions harm the competitive position of the U.S. in many areas of HEDLP research (e.g., radiation-dominated plasmas). Their breadth deserves reconsideration in the context of the long-term strategic interest of the U.S.

What are we saying that's the same as said before?

- Here is the great science …
- Facilities (both experimental and computational) are available now that will enable the study of matter under extreme conditions of temperature and pressure.* That is, we can now design, carry out and analyze such experiments, some of which are far enough away from experience that we can only guess the outcome. We are likely to be surprised with many findings, including the possibility of unexpected applications arising from them.
- In the near future, even greater capability will be available.
- Now is the time to enable this field to grow, taking advantage of both the facilities and the enthusiasm of physicists who would like to use them.

* $> 10^{10} – 10^{11}$ J/m^3

What are we saying that's ***not*** the same as said before?

- There **are** some serious obstacles which need to be overcome ...
- National security concerns and classification are a substantial barrier to the field's growth in academia
  - This affects in particular materials research (opacities and EOS) and computer modeling (radiative hydrodynamics)
- Export control can also form a barrier to the field's growth in academia, especially at universities that do not permit exclusion of any defined class of students from on-campus research
- Open user access – in the style developed within DOE/SC – is critical to building HEDLP
  - This will be a challenge at the NNSA HEDLP facilities

… which brings us to

Questions and discussion